S P E C I F I C A T I O N

SYSTEM AND METHOD FOR CHARACTERIZING THREE-DIMENSIONAL STRUCTURES

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5   CROSS-REFERENCE TO RELATED APPLICATIONS

[0001]   This application claims priority to U.S. Provisional Application Serial No.

60/427,762, entitled "System and Method for Characterization of Small Three Dimensional

Structures," filed on November 20, 2002. Priority to the prior provisional application is

expressly claimed, and the disclosure of the provisional application is hereby incorporated by

10   reference in its entirety.

FIELD OF THE INVENTION

[0002]   The present invention relates generally to metrology and/or process monitoring

systems and more particularly, but not exclusively, to optical metrology and/or process

monitoring systems for characterizing yield limiting deviations and defects during semiconductor

15   processing.

BACKGROUND OF THE INVENTION

[0003]   Semiconductor processing is a well established technology for making

microelectronic devices. This technology involves depositing thin films of insulator (dielectric)

and metallic materials on the surface of semiconductor wafer. These films vary in thickness

20   from a few Angstroms to a few microns depending on what function they serve in the structure

of an electronic device. The device is built layer by layer starting from the surface of the

semiconductor. The transistors, which are the active part of the device, are formed in the

semiconductor and film stacks consisting of alternating metal-dielectric structures are built on

top of the semiconductor. These thin films are etched at specific lithographically defined

1

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locations to form vias or contact holes. These vias or contacts are filled with conducting materials such as metals so that connections can be made from upper layer interconnects to lower layer interconnects. Interconnects connect different points of the device to each other within one plane.

5   [0004]   There are tight tolerances for film thicknesses and lateral dimensions of the structures involved. Any deviation or excursion from a set of predefined design rules can be a serious yield limiting issue in the manufacturing of these devices. For example, if the thickness of a given layer deviates from the required specification, there would be a severe penalty on yield – a wrong film thickness is therefore a yield limiting deviation or defect. These issues have only

10   become more important as integrated circuit processing technology advances to allow smaller device geometries. For this reason, film characterization has proven to be an important part of monitoring the yield and the operation of the device. Current technologies for film characterization include spectroscopic ellipsometry and reflectometry. Both these techniques rely on reflection of light from planar interfaces and they take advantage of changes in Fresnel

15   reflectivity with wavelength and angle of illumination and their application to semiconductor processing is covered under United States Patents Nos. 4,999,014; 5,042,951; 5,181,080; 5,329,357; 5,412,473; 5,596,411; 5,608,526; 5,771,094; 5,747,813; 5,917,594; and 6,323,946. It is important to note that for film characterization, reflectometry and ellipsometry rely on reflection of light from two-dimensional (2D) planes of film interfaces. Recently, a technology

20   called scatterometry, covered under US patents 6429943, 6433878, 6483580, 6451621 has emerged which can use the same hardware as an ellipsometer or a reflectometer for dimensional measurements. For example with these techniques the smallest dimension (critical dimension) printed, may be measured. As the world of microelectronics is moving toward nanotechnology, both critical dimension (CD) metrology and film thickness measurement are playing an

25   increasingly vital role in high performance device fabrication. The devices of the future will require an increasing numbers of lithography masking steps, thereby increasing and accelerating the number of corresponding CD and film measurement steps.

[0005]   Many structures, and their corresponding yield limiting deviations and defects are, in general, three-dimensional (3D). This is true for both the at the transistor level and also at the subsequent metal layers. At the transistor level one would be interested in measuring the sidewall angle, height, and profile of a feature with minimum dimensions. A wrong CD, profile, or sidewall angle would also be a yield limiting deviation or defect.

[0006]   For interconnects, recently, the copper Damascene process has become the preferred technology. In this technology a layer of diffusion barrier material such as TaN is deposited on the walls of the trench and via. This process step is followed by depositing a seed layer of copper on top of the barrier layer. And finally through electroplating a thicker layer of copper fills up the trenches and vias. This process then is followed by the Chemical Mechanical Planarization (CMP). Figs. 1A-B show the top and side views, respectively, of this structure after CMP. Figure 1A shows the copper lines, the diffusion barrier layer and the inter-metal dielectric (IMD) layer separating the conductor lines from each other. In Fig. 1B, the side view additionally shows the trench etch stop, interlayer dielectric (ILD) and the dielectric diffusion barrier and the via for making connection to the lower layer. In Fig. 1C, some of the problems associated with the copper Damascene are captured and some typical thicknesses for the films involved are given. Firstly, the dishing and erosion of the copper is shown. Since copper is a soft material during CMP, the material loses planarity and the surface becomes bowed. This can make lithography of the subsequent steps complicated and can lead to a reduction in yield.

[0007]   The side wall coverage with the barrier material is another major problem. This is because vacuum deposition, while effective on flat surfaces, can be problematic when it comes to high aspect ratio trenches and vias. Proper coverage of the sidewalls with the barrier material can cause the diffusion of the copper and can lead to serious problems, ultimately limiting the fabrication yield. Formation of voids within the copper is another major problem that arises during the electroplating process. Voids such as the one shown in Figure 2 increase the electrical resistance of the trench and via and can lead to high current densities and heating. As is clear, these problems usually are in three dimensions. Prior art ellipsometry and reflectometry fail to

characterize such yield limiting deviations. Therefore, a need clearly exists for characterizing these three-dimensional deviations in conjunction with film characterization and film thickness measurement.

[0008]   In view of the foregoing, a need exists for an improved metrology and/or process

5   monitoring system that overcomes the aforementioned obstacles and deficiencies of currently-available systems.

SUMMARY OF THE INVENTION

[0009]   The various embodiments disclosed herein are directed toward a metrology and/or process monitoring system (herein referred to, separately and collectively, as a "metrology

10   system") that is configured to characterize three-dimensional structures to determine whether the structures have any defects, such as yield limiting deviations or other processing defects.

[0010]   Each of the embodiments comprises a metrology system including a measurement system that is in communication with a processing system. Being configured to characterize a three-dimensional structure formed on a specimen, the metrology system can rotate the

15   measurement system relative to the specimen while the measurement system directs a beam of incident energy toward the specimen. The rotation of the measurement system relative to the specimen is performed along an axis of rotation that preferably is substantially perpendicular to a surface of the specimen and intersects the structure. Propagating toward the specimen substantially at an angle of illumination relative to the axis of rotation, the incident energy

20   rebounds from the specimen as scattered energy, at least a portion of which propagates toward the measurement system.

[0011]   The measurement system also is configured to receive the scattered energy and to produce data signals therefrom, providing the data signals to the processing system. As the relative rotation continues, the measurement system receives scattered energy associated with

25   each of a plurality of rotation angles and produces additional data signals, which likewise are provided to the processing system. Thereby, a spectrum of data signals is produced with respect

to the plurality of rotation angles. Receiving the spectrum of data signals from the measurement system, the processing system is configured to perform an analysis of the data signals to determine whether the structure has any defects, such as yield limiting deviations or other processing defects.

5 **[0012]** Other aspects and features of the various embodiments disclosed herein will become apparent from consideration of the following description taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] Fig. 1A is a top view of a prior art Copper Damascene structure after a Chemical

10 Mechanical Planarization (CMP) process.

[0014] Fig. 1B is a side view of the prior art Copper Damascene structure of Fig. 1A.

[0015] Fig. 1C illustrates typical problems associated with prior art Copper Damascene structures.

[0016] Fig. 2 is an exemplary block diagram of an embodiment of a metrology and/or

15 process monitoring system ("metrology system") for characterizing three dimensional structures.

[0017] Fig. 3 is an exemplary block diagram illustrating one embodiment of a measurement system for the metrology system of Fig. 2.

[0018] Fig. 4A is a detail drawing illustrating one embodiment of an energy source for the measurement system of Fig. 3.

20 **[0019]** Fig. 4B is a detail drawing illustrating an alternative embodiment of the energy source of Fig. 4A.

[0020] Fig. 5A is a detail drawing illustrating one embodiment of an energy detector for the measurement system of Fig. 3.

[0021] Fig. 5B is a detail drawing illustrating an alternative embodiment of the energy

25 detector of Fig. 5A.

[0022]   Fig. 6A is a top view of the metrology system of Fig. 3 and illustrates a dark field

detection configuration of the energy source of Figs. 4A-B and the energy detector of Figs. 5A-

B.

[0023]   Fig. 6B is a top view of the metrology system of Fig. 3 and illustrates a bright field

5   detection configuration of the energy source of Figs. 4A-B and the energy detector of Figs. 5A-

B.

[0024]   Fig. 7A is a detail drawing illustrating one embodiment of a processing system for the

metrology system of Fig. 3.

[0025]   Fig. 7B is a detail drawing illustrating an alternative embodiment of the processing

10   system of Fig. 7A.

[0026]   Fig. 8 is an exemplary block diagram illustrating an alternative embodiment of the

measurement system of Fig. 3.

[0027]   Fig. 9 is an exemplary three-dimensional structure for illustrating the operation of the

metrology system of Fig. 2.

15   [0028]   Fig. 10 illustrates an exemplary two-dimensional power spectrum characterization of

the structure of Fig. 9.

[0029]   Figs. 11A-B illustrate exemplary three-dimensional power spectrum characterizations

of the structure of Fig. 9.

[0030]   Fig. 12 illustrates an electric field of incident energy provided by the energy source of

20   Figs. 4A-B.

[0031]   Fig. 13A illustrates the incident energy of Fig. 12 having a S-polarization and

propagating substantially perpendicularly toward the grating lines of a grating structure.

[0032]   Fig. 13B illustrates the incident energy of Fig. 13A propagating toward grating

structure substantially in parallel with the grating lines.

25   [0033]   Fig. 13C illustrates the incident energy of Fig. 12 having a P-polarization and

propagating substantially perpendicularly toward the grating lines of a grating structure.

[0034] Fig. 13D illustrates the incident energy of Fig. 13C propagating toward grating structure substantially in parallel with the grating lines.

[0035] Fig. 14A is an exemplary block diagram illustrating an alternative embodiment of the metrology system of Fig. 2.

5 **[0036]** Fig. 14B is a detail drawing illustrating one embodiment of a beam-formation system for the metrology system of Fig. 14A.

[0037] Fig. 15 illustrates another alternative embodiment of the metrology system of Fig. 2.

[0038] It should be noted that the figures are not drawn to scale and that elements of similar structures or functions are generally represented by like reference numerals for illustrative 10 purposes throughout the figures. It also should be noted that the figures are only intended to facilitate the description of the preferred embodiments of the present invention. The figures do not describe every aspect of the present invention and do not limit the scope of the invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0039] Since current metrology and/or process monitoring systems (herein referred to, 15 separately and collectively, as "metrology systems") are inadequate for complex structures, can be destructive, and can prove difficult and costly to implement, a metrology system for characterizing three dimensional structures that is configured to rotate relative to the three dimensional structures during characterization can prove much more desirable and provide a basis for a wide range of industrial applications, such as the characterization of yield limiting 20 deviations and defects during semiconductor processing. This result can be achieved, according to one embodiment disclosed herein, by employing a metrology system 100 as shown in Fig. 2.

[0040] The exemplary metrology system 100 includes a measurement system 200 that is coupled with, and configured to communicate with, a processing system 300. Being configured to characterize a three-dimensional structure 410 formed on a specimen 400, the metrology 25 system 100 can rotate the measurement system 200 relative to the specimen 400 while the measurement system 200 directs a beam of incident energy 500 toward the specimen 400. As

illustrated in Fig. 2, the rotation of the measurement system 200 relative to specimen 400 is performed along an axis of rotation AR that preferably is substantially perpendicular to an external surface 420 of the specimen 400 and intersects the structure 410. Propagating toward the specimen 400 substantially at an angle of illumination (or angle of incidence) θ relative to the

5 axis of rotation AR, the incident energy 500 rebounds from the specimen 400 as scattered energy 520. The scattered energy 520 rebounds from the specimen 400 in a plurality of directions as illustrated in Fig. 2. At least a portion of the scattered energy 520 propagates toward the measurement system 200.

[0041]   The measurement system 200 also is configured to receive the portion of the scattered

10 energy 520 and to produce data signals (not shown) therefrom, providing the data signals to the processing system 300. As the relative rotation continues, the measurement system 200 receives scattered energy 520 associated with each of a plurality of rotation angles (or azimuthal angles) ϕ and produces additional data signals, which likewise are provided to the processing system 300. Thereby, a spectrum of data signals is produced with respect to the rotation angle ϕ. Receiving

15 the spectrum of data signals, in whole or in part, from the measurement system 200, the processing system 300 is configured to perform an analysis of the data signals to determine whether the structure 410 has any defects, such as yield limiting deviations or other processing defects. The processing system 300 can analyze the data signals in any suitable manner, such as by comparing the data signals with one or more mathematical models (not shown) of the

20 structure 410 and/or by using a neural network that has been trained to identify structural defects.

[0042]   Turning to Fig. 3, the metrology system 100 is shown as having a measurement system 200' that comprises an energy source 210 and an energy detector 220. Typically being coupled and preferably being substantially fixedly coupled, the energy source 210 and the energy detector 220 are approximately uniformly disposed about, and substantially in axial alignment

25 with, the axis of rotation AR. Thereby, the energy source 210 and the energy detector 220 are configured to rotate substantially as a unit around the axis of rotation AR relative to the specimen 400.

[0043] As will be discussed in more detail below with reference to Figs. 6A-B, the energy source 210 and the energy detector 220 can be provided in any appropriate configuration such that the energy detector 220 is configured to receive the scattered energy 520 (shown in Fig. 2). The suitability of a particular configuration may depend, at least in part, upon the nature of the

5   specific application for which the metrology system 100 is to be utilized. Illustrative factors for identifying suitable configurations include the dimensions and complexity of the structure 410 being characterized, the materials from which the structure 410 is formed, and the desired precision of the characterization results. The measurement system 200' as shown in Fig. 3 is provided in the manner discussed in more detail below with reference to Fig. 6B and is

10   configured to receive the incident energy 500 that reflects from the specimen 400 as reflected energy 500'.

[0044] The energy source 210 can be any type of energy source that can provide a suitable beam of incident energy 500, which preferably comprises electromagnetic radiation. Illustrative energy sources include monochromatic light sources, such as a gas laser or a solid state laser

15   diode, and broadband sources, such as a xenon-arc lamp, as well as x-ray, ultraviolet, infra-red, and/or microwave energy. Being configured to direct the beam of incident energy 500 toward the specimen 400 in the manner discussed above with reference to the measurement system 200 (shown in Fig. 2), the energy source 210 can be coupled with, and can communicate with, the processing system 300 as illustrated in Fig. 3. The processing system 300, for example, can be

20   configured to activate and deactivate the energy source 210 and/or to control the angle of illumination θ relative to the axis of rotation AR. The angle of illumination θ can comprise any suitable angle for directing the incident energy 500 toward the specimen 400. Therefore, the angle of illumination θ can be a substantially-fixed predetermined angle or can be adjustable among a plurality of predetermined angles within a predetermined range of angles.

25   **[0045]** Similarly, the processing system 300 can control a predetermined wavelength λ of the incident energy 500 provided by the energy source 210. The incident energy 500 has at least one predetermined wavelength λ that preferably is substantially within a predetermined range of

wavelengths. Stated somewhat differently, the wavelength λ of the incident energy 500 can

comprise a substantially-fixed predetermined wavelength or can vary among a plurality of

predetermined wavelengths, such as a sweep of successive wavelengths, each being substantially

within the predetermined range. The incident energy 500 also can be polychromatic energy,

5   such as white light, simultaneously comprising a plurality of wavelengths λ. Although the

incident energy 500 generally is shown and described herein as comprising optical waves and/or

microwaves for purposes of illustration, it is understood that the wavelength λ of the incident

energy 500 can be any suitable wavelength within any predetermined range and is not limited to

the illustrated embodiments.

10   **[0046]**   For example, the incident energy 500 can comprise radio waves having a frequency

of up to approximately three gigahertz (<3GHz) or microwaves having a frequency in a range

substantially between three hundred megahertz and three hundred gigahertz (300MHz–300GHz).

Likewise, the frequency of the incident energy 500 can be substantially within the infrared band

having a wavelength between approximately seven hundred nanometers and one hundred

15   micrometers (700nm–100μm), the visible band having a wavelength between approximately four

hundred and seven hundred nanometers (400nm-700nm), the ultraviolet band having a

wavelength between approximately four and four hundred nanometers (4nm–400nm), or the soft

or hard x-ray band having a wavelength between approximately one picometer and ten

nanometers (1pm-10nm). The selection of the predetermined wavelength λ and/or the

20   predetermined range may depend, at least in part, upon the nature of the specific application for

which the metrology system 100 is to be utilized in the manner discussed above. If comprising

polychromatic light energy, the incident energy 500 can have a plurality of wavelengths λ within

a range of between approximately one hundred and ninety nanometers and one and one-half

microns (190 nm-1.5 microns), or a portion thereof, simultaneously.

25   **[0047]**   It will be appreciated that the energy source 210 can include a beam-formation

system (or beam-conditioning system) 215 as shown in Figs. 4A-B. Being disposed substantially

between the energy source 210 and the specimen 400, the beam-formation system 215 is

configured to receive output energy 510 (shown in Fig. 4B) from the energy source 210 and to

convert the output energy 510 into the beam of incident energy 500. As illustrated in Fig. 14B,

for example, the beam-formation system 215 can include one or more polarization systems

215A, beam-splitting systems 215B, modulation systems 215C, 215G, mirrors 215D, 215F,

5   wave plates 215E, beam-combining systems 215H, and/or any other suitable components.

Exemplary modulation systems include phase or intensity modulation systems, such as an

acousto-optic modulation (AOM) system. The beam-formation system 215 can be disposed

substantially within the energy source 210 as illustrated in Fig. 4A or can be separate from the

energy source 210 as shown in Fig. 4B.

10   **[0048]**   Figs. 5A-B illustrate the energy detector 220 for the measurement system 200'

(shown in Fig. 3). The energy detector 220 can comprise any type of energy detector that is

suitable for detecting and/or receiving the reflected energy 500'. If the energy source 210 is a

laser or light emitting diode system, for example, one or more photomultiplier tubes (PMT)

and/or photodiodes can be used as the energy detector 220. Likewise, the energy detector 220

15   can comprise a wavelength dispersive element, such as a prism or grating, and a charge-coupled

device (CCD) or photodiode array when the energy source 210 is a broadband or polychromatic

source. Furthermore, the energy detector 220 can include one or more polarization elements,

such as a polarization system 215A (shown in Fig. 14B) and/or a wave plate 215E (shown in Fig.

14B). The energy detector 220 likewise can comprise demodulator circuitry after the reflected

20   energy 500' has been detected. The energy detector 220 also is coupled with, and can

communicate with, the processing system 300. For example, preferably being configured to

produce data signals from the reflected energy 500', the energy detector 220 configured to

provide the data signals to the processing system 300 in the manner discussed above with regard

to the measurement system 200 (shown in Fig. 2).

25   **[0049]**   As desired, an energy-collection system (or collection system) 225 can be disposed

substantially between the specimen 400 and the energy detector 220 as illustrated in Figs. 5A-B.

The energy-collection system 225 is configured to receive the reflections of the incident energy

500 from the specimen 400 and to convert these reflections into the reflected energy 500'. In the manner discussed above with regard to the beam-formation system 215 (shown in Figs. 4A-B), the energy-collection system 225 can include any number of additional systems such as one or more polarization systems 215A (shown in Fig. 14B) and/or wave plates 215E (shown in Fig.

5   14B). As shown in Fig. 5A, the energy-collection system 225 can be disposed substantially within the energy detector 220, or the energy-collection system 225 can be separate from the energy detector 220 as shown in Fig. 5B.

[0050]   One configuration of the energy source 210 and the energy detector 220 of the measurement system 200' (shown in Fig. 3) is shown in Figs. 6A-B. As illustrated in Fig. 6A,

10   the beam of incident energy 500 propagates from the energy source 210, defining an axis of incidence AI. The energy detector 220 can be displaced from the axis of incidence AI by an angular offset α. By being displaced from the axis of incidence AI by the angular offset α, the energy detector 220 is configured to detect and/or receive non-specular scatterings of the incident energy 500 from the specimen 400 as the scattered energy 520. It will be appreciated

15   that the angular offset α can comprise any suitable angular offset and preferably is selected to enhance the sensitivity of the metrology system 100 to one or more preselected features, such as the structure 410 (shown in Figs. 2 and 3) of the specimen 400 to be characterized. This configuration sometimes is referred to as a dark field detection configuration.

[0051]   It will be appreciated that, if the surface 420 of the specimen 400 is substantially

20   smooth, no significant dark field scattering with result from the reflection of the incident energy 500 from the surface 420. As such, when the measurement system 200' is provided in the dark field detection configuration, the scattered energy 520 primarily comprises energy scattered from the three-dimensional structure 410 formed on the specimen 400. The structure 410 therefore can be characterized by the scattered energy 520 rebounded from the structure 410, and any

25   defects in the structure 410 can be detected.

[0052]   When the angular offset α is substantially equal to zero, the energy detector 220 is substantially in axial alignment with the axis of incidence AI. In contrast to the dark field

detection configuration of the measurement system 200', the energy detector 220 is configured to detect and/or receive specular scattering or reflection of the incident energy 500 from the specimen 400 as the reflected energy 500'. This configuration may be referred to as a bright field detection configuration and is illustrated in Fig. 6B. The energy source 210 and the energy

5   detector 220 preferably are substantially fixedly coupled such that the angular offset α is approximately maintained during the rotation of the measurement system 200' relative to the specimen 400. As illustrated in Figs. 6B, the energy source 210 and the energy detector 220 are substantially fixedly coupled via a coupling system 230, which can comprise any type of mechanical coupling system, including one or more brackets and/or platforms, such as the

10   rotatable platform 710 shown in Fig. 7B.

[0053]   Since the energy source 210 and the energy detector 220 are substantially axially aligned, the incident energy 500 from the energy source 210 and the reflected energy 500' received by the energy detector 220 define a plane of incidence PI as shown in Figs. 6B and 8. Since the axis of rotation AR preferably is substantially perpendicular to the surface 420 of the

15   specimen 400, the plane of incidence PI likewise preferably is substantially perpendicular to the surface 420 as illustrated in Fig. 9. Therefore, when the energy source 210 and the energy detector 220 rotate about the axis of rotation AR (shown in Fig. 9), the plane of incidence PI likewise rotates about the axis of rotation AR.

[0054]   Further, the phase of the incident energy 500 can be measured when the energy

20   source 210 and the energy detector 220 are in the bright field detection configuration. For example, the metrology system 100 can include one or more beam-splitting systems 215B (shown in Fig. 14B) and/or beam-combining systems 215H (shown in Fig. 14B) for branching off a portion of the incident energy 500 to form a reference beam of incident energy (not shown). The reference beam can be directed toward the energy detector 220 such that the reference beam

25   interferes with the reflected energy 500' Similarly, when the reflected energy 500' includes at least two components, such as a S-polarized component and a P-polarized component, the components of the reflected energy 500' can be interfered to provide a phase difference between

the two components. It is understood that, as desired, the metrology system 100 can include a

second energy source (not shown) that is configured to provide the reference beam.

[0055]   One embodiment of a processing system 300' for metrology systems 100' is

illustrated in Fig. 7A. The processing system 300' is configured to receive the data signals from

5   the measurement system 200' and to analyze the data signals to determine whether the structure

410 (shown in Fig. 2) formed on the specimen 400 has any defects. As shown in Fig. 7A, the

processing system 300' comprises a data acquisition system 310', a central processing system

320', and a memory system 330'. The data acquisition system 310' is configured to receive the

data signals and, as desired, to convert the data signals into digital data (not shown). In a

10   preferred embodiment, the data acquisition system 310' includes at least one analog-to-digital

conversion (ADC) system for digitizing the data signals.

[0056]   Being configured to perform the analysis of the digital data, the central processing

system 320' can comprise any type of processing system, such as one or more central processing

units (CPUs) and/or digital signal processors (DSPs), and is configured to communicate with the

15   data acquisition system 310' and the memory system 330'. The central processing system 320'

thereby can receive the digital data from acquisition system 310' and/or the memory system

330'. In other words, the central processing system 320' can perform the analysis of the digital

data in real-time and/or can store the digital data in the memory system 330' for later retrieval

and analysis. The digital data preferably is stored in the memory system 330' such that the

20   association between the digital data and the rotation angle ϕ is substantially maintained. If each

rotation angle ϕ is associated with a memory register (not shown), for example, the digital data

for each rotation angle ϕ can be stored in the relevant memory register. Similarly, the digital

data and the associated rotation angle ϕ can be stored in the memory system 330' in the form of a

look-up table.

25   [0057]   Comprising any suitable type of memory system, the memory system 330' can

include volatile memory and/or non-volatile memory of any kind and can be configured to store

and provide other types of information. For example, the central processing system 320' can

perform the data analysis by receiving and executing a series of instructions, which can be provided in the form of instruction code, such as software or firmware, that is stored in the memory system 330'. The partial and/or complete results of the analysis likewise can be stored in, and retrievable from, the memory system 330'. As desired, the central processing system

5   320' can analyze the digital data as the data signals are successively received by the processing system 300', and/or the analysis can be delayed until substantially the complete spectrum of data signals has been received.

[0058]   The central processing system 320' can perform the analysis of the digital data in any suitable manner. For example, the analysis of the digital data can be performed via a neural

10   network (not shown). The neural network can be trained to identify preferred spectra of digital data by examining a plurality of sample specimens 400. By analyzing a wide range of good and bad sample specimens 400, the neural network can "learn" to identify spectra associated with preselected structural defects.

[0059]   In another embodiment, the central processing system 320' is configured to perform

15   the data analysis by comparing the digital data with one or more mathematical models (not shown) of the structure 410 as illustrated by the processing system 300" of the metrology system 100" shown in Fig. 7B. Being provided substantially in the manner discussed above with reference to the processing system 300' (shown in Fig. 7A), the processing system 300" comprises a data acquisition system 310", a central processing system 320", and a memory

20   system 330" and further includes a modeling system 340". As desired, the modeling system 340" can be combined with, or substantially separate from, the memory system 330".

[0060]   The modeling system 340" is configured to provide at least one mathematical model of the structure 410. Each mathematical model typically is calculated based upon input parameters regarding ideal dimensions of the structure 410 as well as other information, such as

25   user-provided information. Upon receiving the digital data, the central processing system 320" is configured to compare the digital data with the mathematical model in any suitable manner, such as by performing a minimization procedure, such as a minimization procedure involving

nonlinear regression. Similarly, model data (not shown) can be precalculated for each mathematical model and stored in the modeling system 340", preferably in the form of a look-up table. The central processing system 320" thereby can perform the data analysis by comparing the digital data with the model data. The processing system 300 (shown in Fig. 2) is shown and

5   described herein as comprising the processing system 300' in Fig. 7A and the processing system 300" in Fig. 7B for purposes of illustration only. The processing system 300 can be any suitable type of processing system and is not limited to the illustrated embodiments. Likewise, it is understood that the measurement system 200 (shown in Fig. 2) can comprise any suitable type of measurement system and is not limited to the exemplary measurement systems 200', 200" shown

10   and described with reference to Figs. 3 and 6A and Fig. 7B, respectively.

[0061]   It also will be appreciated that the incident energy 500 and/or the reflected energy 500' can propagate between the measurement system 200' substantially directly as illustrated in Fig. 7A or via one or more intermediate systems, such as the focusing system 800 shown in Fig. 7B. Being disposed substantially between the measurement system 200' and the specimen 400,

15   the focusing system 800 is configured to focus the incident energy 500, the reflected energy 500' and/or the scattered energy 520 (shown in Figs. 2 and 8). Illustrative focusing system 800 are disclosed in United States Patent No. 5,604,334, issued to Finarov, and United States Patent No. 6,124,924, issued to Feldman et al., each of which are hereby expressly incorporated herein by reference.

20   [0062]   If the energy source 210 is a monochromatic light source, such as a laser, for example, the focusing system 800 can be a lens or a lens system, such as a microscope objective; whereas, the focusing system 800 can comprise radiation-reflective focusing optics when the energy source 210 is a broadband source. Likewise, the focusing system 800 can include a bent crystal if the energy source 210 emits incident energy 500 with a preselected wavelength λ that is

25   substantially in the x-ray band. As desired, the focusing system 800 can include the beam-formation system 215 discussed in more detail above with regard to Figs. 4A-B and/or the energy-collection system 225 discussed in more detail above with reference to Figs. 5A-B.

[0063]   Returning to Fig. 3, the metrology system 100 can further include a platform 600 for

supporting the specimen 400. The platform 600 can comprise any suitable type of platform, such

as a vacuum chuck or an electrostatic chuck, such that the specimen 400 is secured substantially

in place. In the manner described above, depending, at least in part, upon the nature of the

5   specific application for which the metrology system 100 is to be utilized, the platform 600 can be

a motorized translation platform, or any other suitable mechanical device or system known in the

art. Specifically, a motorized translation stage can be employed such that different portions,

such as multiple structures 410, of the specimen 400 can be characterized by the metrology

system 100. Although illustrated in Fig. 3 as being uncoupled from the measurement system

10   200' and the processing system 300, it is understood that the platform 600 can be coupled with,

and configured to communicate with, the measurement system 200' and/or the processing system

300 as desired.

[0064]   The relative rotation between the measurement system 200' and the specimen 400 can

be achieved in any manner such as by rotating the measurement system 200'. For example, Fig.

15   7B illustrates a rotation system 700 that is configured to rotate the measurement system 200'

substantially about the axis of rotation AR to achieve the relative rotation between the

measurement system 200' and the specimen 400. As shown in Fig. 7B, the rotation system 700

comprises a rotatable platform 710 and a control system 720. The rotatable platform 710 is

fixedly coupled with the energy source 210 and the energy detector 220 of the measurement

20   system 200'. The control system 720 can comprise any suitable type of control system, such as a

motor, and, as shown in Fig. 7B, can be coupled with the processing system 300". Thereby, the

operation of the control system 720, and therefore the rotation of the measurement system 200',

is controllable via the processing system 300".

[0065]   The control system 720 can further include an encoding system (not shown) that is

25   configured to produce a rotational data signal (not shown) that represents the rotation angle ϕ of

the rotatable platform 710 and to provide the rotational data signal to the processing system

300". The rotational data signal can provide feedback to the processing system 300" when the

processing system 300" is configured to control the rotation of the measurement system 200'.

Further, the processing system 300" can utilize the rotational data signal to associate the relevant

rotation angle φ with the relevant data signal and/or the digital data produced therefrom, for

example, when storing the digital data in the memory system 330" in the manner discussed in

5   more detail above with reference to the processing system 300".

[0066]   Although shown and described as comprising the rotation system 700 in Fig. 7B for

purposes of illustration, it is understood that the relative rotation between the measurement

system 200 and the specimen 400 can be achieved by way of any suitable rotation system and is

not limited to the illustrated embodiment. For example, the relative rotation can be carried out

10   electronically, such as by employing a measurement system 200 as shown in Fig. 8 that

comprises an array 210' of energy sources 210A-F and an array 220' of energy detectors 220A-

F. The array 210' can comprise any number of energy sources 210A-F, each being provided in

the manner set forth in more detail above with reference to Figs. 3 and 4A-B; Likewise, the

array 220' can include any number of energy detectors 220. Each of the energy detectors 220A-

15   F in the array 220' are provided in the manner set forth in more detail above with reference to

Figs. 3 and 5A-B. Each of the arrays 210', 220' can be disposed, partially or substantially

completely, around the specimen 400 in substantially any suitable arrangement or configuration,

and each energy source 210 in the array 210' is associated with at least one energy detector 220

in the array 220'.

20   [0067]   As shown in Fig. 8, the arrays 210', 220' are provided in the bright field detection

configuration (shown in Fig. 6B) and are partially disposed around the specimen 400. Energy

source 210A is configured to direct incident energy 500A toward the specimen 400 and is

associated with energy detector 220A. The energy detector 220A is configured to receive a

portion of the incident energy 500A that reflects from the specimen 400 as reflected energy

25   500A'. Being associated with energy detector 220B, energy source 210B can direct incident

energy 500B toward the specimen 400 at a predetermined angle ϕ_{AB} relative to the incident

energy 500A provided by the energy detector 220A. A portion of the incident energy 500B that

reflects from the specimen 400 is received by the energy detector 220B as reflected energy

500B'. Similarly, energy sources 210C-F respectively direct incident energies 500C-F toward

the specimen 400 at predetermined angles ϕ_{BC}, ϕ_{CD}, ϕ_{DE}, and ϕ_{EF} relative to the incident energies

500B-E, respectively. The incident energies 500C-F reflect from the specimen 400 as reflected

5   energies 500C-F', a portion of which is received by energy detectors 220C-F, respectively.

[0068]   The predetermined angles ϕ_{AB}, ϕ_{BC}, ϕ_{CD}, ϕ_{DE}, and ϕ_{EF} can comprise any suitable angle

and preferably are substantially equal. Similarly, the energy detectors 220A-F preferably are

configured to provide the incident energies 500A-F with substantially the same characteristics.

Thereby, when the energy detectors 220A-F are successively activated, the incident energies

10   500A-F are successively directed toward the specimen 400, and the energy detectors 220A-F

successively receive the reflected energies 500A-F' such that the measurement system 200 is

virtually rotated relative to the specimen 400.

[0069]   Upon receiving the reflected energies 500A-F', the measurement system 200 can

produce the spectrum of data signals therefrom and provide the spectrum of data signals to the

15   processing system 300 (shown in Fig. 3) in the manner discussed in more detail above.

Likewise, the processing system 300 can perform an analysis of the spectrum of data signals in

the manner set forth above to determine whether the structure 410 has any defects. Electronic

rotation can reduce the time required to produce the spectrum of data signals, which time

reduction is highly desirable for in line metrology and process monitoring of semiconductor

20   wafers during processing.

[0070]   It will be appreciated that electronic rotation likewise can be performed with the

arrays 210', 220' in the dark field detection configuration discussed above with reference to Fig.

6A. Furthermore, by associating more than one energy detector 220 with an energy source 210,

the measurement system 200 is configured to be in both the bright field and the dark field

25   detection configurations. If the energy detectors 220A, 220C are associated with the energy

source 210A, for example, the measurement system 200 is configured to receive and analyze the

reflected energy 500A' via the energy detector 220A and the scattered energy 520 (shown in Fig.

2) via the energy detector 220C. Thereby, the metrology system 100 substantially

simultaneously receive and analyze bright field and dark field data signals.

[0071]   The details of the operation of the metrology system 100" will be presently discussed

with reference to Figs. 6B, 7B, 8, and 9. Although a bright field detection configuration of the

5   energy source 210 and the energy detector 220 as shown in Fig. 6B is assumed for purposes of

illustration, it is understood that the present discussion can equally apply to a dark field detection

configuration of Fig. 6A. Fig. 9 is a three-dimensional view of an exemplary structure 410

formed on the specimen 400. For purposes of simplicity, the exemplary structure 410 is

illustrated in Fig. 9 as a plurality of substantially parallel trenches 430 formed in the specimen

10   400 and defined by internal surfaces 440. It is understood, however, that any surface in which

the reflectivity or impedance is a function of angle can be characterized by the metrology system

100". In the manner discussed in more detail above with reference to Fig. 7B, the metrology

system 100" is configured to rotate the measurement system 200 along the axis of rotation AR,

which preferably is substantially perpendicular to the external surface 420 of the specimen 400

15   and intersects the structure 410.

[0072]   In operation, the energy source 210 provides the beam of incident energy 500, which

propagates toward the specimen 400 substantially at the angle of illumination θ relative to the

axis of rotation AR. Upon reaching the specimen 400, the incident energy 500 reflects from the

specimen 400. As shown in Fig. 9, some of the incident energy 500 rebounds from the specimen

20   400 in various directions as scattered energy 520; whereas, a portion of the incident energy 500

reflects toward the energy detector 220 as reflected energy 500' in the manner discussed in more

detail above with reference to Fig. 2. The energy detector 220 receives and detects the reflected

energy 500' and produces data signals therefrom. Although the data signals can be any suitable

type of information regarding the reflected energy 500', such as an amplitude, a frequency, a

25   phase change, and/or a power level, the data signals are shown and described as comprising a

power level of the reflected energy 500' for purposes of this example.

[0073]   As the metrology system 100" rotates the energy source 210 and the energy detector

220 about the axis of rotation AR, the incident energy 500 propagates toward, and therefore

reflects from, the external and internal surfaces 420, 440 from different rotation angles ϕ. The

power level of the reflected energy 500' as received by the energy detector 220 therefore can

5   vary as a function of the rotation angle ϕ. For instance, when the energy source 210 and the

energy detector 220 are substantially perpendicular to the trenches 430, a relatively large portion

of the incident energy 500 is reflected by the internal surfaces 440 as scattered energy 520, and

the power level of the reflected energy 500' as measured by the energy detector 220 is relatively

low. In contrast, a lesser portion of the incident energy 500 is reflected by the internal surfaces

10   440 as scattered energy 520 when the energy source 210 and the energy detector 220 are

substantially in parallel with the trenches 430. The energy detector 220 therefore measures

reflected energy 500' with a higher power level.

[0074]   In the manner described in more detail above with reference to Fig. 3, the

measurement system 200' produces a spectrum of measured power data signals from the

15   measured power levels. The measurement system 200' provides the spectrum of measured

power data signals as well as the rotational data signals produced by the rotation system 700 to

the processing system 300". Upon receiving the spectrum of measured power data signals and

the rotational data signals, the processing system 300" produces digital measured power data

therefrom, which digital measured power data is associated with the relevant rotation angles ϕ, in

20   the manner discussed in more detail above with reference to Fig. 7A. Thereby, the measured

power spectrum PS comprises the measured power level as a function of rotation angles ϕ and is

illustrated in Fig. 10 is produced.

[0075]   The modeling system 340" of the processing system 300" preferably includes at least

one mathematical model of the structure 410 of Fig. 9. Since the measurement system 200' is

25   configured to measure the power level of the reflected energy 500' in this example, the relevant

mathematical model likewise comprises the measured power level as a function of rotation

angles ϕ and is illustrated as a model power spectrum MS in Fig. 10. The processing system

300" performs an analysis of the exemplary structure 410 of Fig. 9 by comparing the measured

power spectrum PS with the model power spectrum MS. Thereby, the metrology system 100"

can determine whether the structure 410 has any defects.

[0076]   It will be appreciated that the operation of the metrology system 100" can be

5   modified in accordance with the nature of the specific application for which the metrology

system 100" is to be utilized. Illustrative factors for identifying suitable configurations include

the dimensions and complexity of the structure 410 being characterized, the materials from

which the structure 410 is formed, and the desired precision of the characterization results. By

the adjusting the operation of the metrology system 100", the metrology system 100" can be

10   configured to analyze more complex structures 410, to increase the precision of the

characterization results, to more quickly characterize the structure 410, and to yield additional

information with regard to the structure 410.

[0077]   For example, the metrology system 100" can be configured to analyze a different

number of data signals when characterizing the structure 410. The number of data signals can be

15   adjusted by modifying the range of the rotation angle ϕ by which the metrology system 100"

rotates the measurement system 200" relative to the specimen 400 and/or by changing the

number of measurement that measurement system 200" makes per revolution relative to the

specimen 400. The range of rotation angles ϕ can comprise any suitable range of angles,

including ranges that exceed a complete revolution of the revolution of the measurement system

20   200" relative to the specimen 400. Stated somewhat differently, the range of rotation angles ϕ

can be greater than, less than, or substantially equal to a complete revolution of three hundred

and sixty degrees (360°). By increasing the number of data signals, the metrology system 100"

can be configured to analyze more complex structures 410 and/or increase the precision of the

characterization results.

25   [0078]   The operation of the metrology system 100" likewise can be modified by permitting

other operational parameters of the metrology system 100", such as the angle of illumination θ,

the polarization of the incident energy 500, and/or the wavelength λ (shown in Fig. 3) of the

incident energy 500, to be adjustable. Although each was presumed to be substantially constant in the above example, the angle of illumination θ and/or the wavelength λ of the incident energy 500 can be adjustable. In the manner discussed in more detail above with reference to Fig. 3, the angle of illumination θ can be adjustable within a predetermined range of angles. Likewise,

5   when the incident energy 500 comprises electromagnetic radiation, for example, the wavelength λ of the incident energy 500 can vary among a plurality of predetermined wavelengths, such as a sweep of successive wavelengths, each being substantially within a predetermined range in the manner discussed above with regard to Fig. 3.

[0079]   The angle of illumination θ and/or the wavelength λ of the incident energy 500 can be

10   adjustable via the processing system 300" and/or independently of the processing system 300". In addition to receiving the data signals and the rotational data signal, the processing system 300" also can receive one or more control signals (not shown) that represent the angle of illumination θ and/or the wavelength λ of the incident energy 500. These control signals can be provided, and associated with the data signals, substantially in the manner discussed above with

15   regard to the rotational data signals. Furthermore, the control signals can provide feedback to the processing system 300" when the processing system 300" is configured to control the angle of illumination θ and/or the wavelength λ of the incident energy 500.

[0080]   The angle of illumination θ and/or the wavelength λ of the incident energy 500 can be adjustable relative to the rotation angle φ. Stated somewhat differently, the metrology system

20   100" can be configured to adjust the rotation angle φ, the angle of illumination θ, and/or the wavelength λ either in isolation or substantially simultaneously in any combination. For example, the angle of illumination θ and/or the wavelength λ of the incident energy 500 can be held substantially fixed for a substantially complete revolution of the measurement system 200" relative to the specimen 400. The angle of illumination θ and/or the wavelength λ of the incident

25   energy 500 likewise can be varied as the measurement system 200" rotates relative to the specimen 400. Figs. 11A-B provide exemplary three-dimensional measured power spectrum characterizations PS', PS" of the structure 410 shown in Fig. 9. By permitting other operational

parameters of the metrology system 100" to be adjustable, the metrology system 100" can be configured to analyze more complex structures 410 and/or increase the precision of the characterization results.

[0081]   Figure 11 illustrates an electric field E of the incident energy 500 incident on the

5   surface 420 and is discussed with reference to the metrology system 100 shown in Fig. 3. As shown in Fig. 12, the surface 420 includes a grating 450. The incident energy 500 comprises a propagating wave with a S-type polarization such that the electric field E is substantially perpendicular to the plane of incidence PI (shown in Fig. 9) defined by the incident energy 500 and the reflected energy 500'. As the energy source 210 rotates though the rotation angle ϕ

10   relative to the specimen 400, the electric field E on the surface 420 of the specimen 400 forms an angle ϕ' relative to the grating 450, which angle ϕ' is approximately equal to the rotation angle ϕ. It will be appreciated that, for each angle ϕ', the surface 420 can have a different impedances at microwave frequencies and a different reflectivities at optical and/or X-ray wavelengths λ.

[0082]   For surfaces 420 that are substantially smooth and isotopic, the field boundary

15   conditions are approximately the same for each rotation angle ϕ at which these surfaces 420 are being interrogated. The field boundary conditions however can differ for each rotation angle ϕ if the surface 420, such as the grating 450 shown in Fig. 12, is not substantially smooth and isotopic. These differences in the field boundary conditions can result in a different reflectivity for the surface 420 for each rotation angle ϕ. Since these differences exist in the phase and/or the

20   amplitude of the complex reflection coefficient, the term "reflectivity" can refer to the usage of the phase and/or the intensity. As such, intensity and/or phase spectra can be obtained with respect to the angle ϕ', and, furthermore, such spectra can be obtained with different input polarizations.

[0083]   It will be appreciated that the grating 450 can be viewed as a plurality of closely-

25   spaced, coupled electromagnetic waveguides. When the incident energy 500 reaches the surface 420, a wave (not shown) is launched in these waveguides, and any associated coupling and resonances can be a function of the characteristics of the incident energy 500. The

characteristics of the incident energy 500 include the angle of illumination θ, rotation angle φ, and the polarization of the incident energy 500. Further, in spectroscopic reflectometry and ellipsometry, a change in the angle of illumination θ and/or the wavelength λ (shown in Fig. 3) of the incident energy 500 can produce a change in the spectrum even if the surface 420 is

5 substantially smooth and isotopic. Here, on the other hand, a change in the spectrum with respect to the rotation angle φ will result only if the surface 420 includes the grating 450 or any other three-dimensional structure, such as structure 410 (shown in Fig. 2). The three-dimensional properties of the grating 450 therefore are being analyzed rather than the two-dimensional properties of the surface 420.

10 **[0084]** Figs. 13A-D illustrate the polarization of the electric field E of the incident energy 500 and is discussed with reference to the metrology system 100 shown in Fig. 3. As illustrated in Figs. 13A-D, the surface 420 includes the grating 450, which comprises a plurality of substantially parallel grating lines 450'. Turning to Fig. 13A, the incident energy 500 is shown as having the electric field E with S-polarization and as propagating toward the grating 450 at an

15 rotation angle φ that is substantially equal to zero degrees (0°). In other words, the incident energy 500 is substantially perpendicular to the grating lines 450'. The electric field E of the incident energy 500 therefore is substantially parallel to the grating lines 450'. The incident energy 500 illustrated in Fig. 13B likewise has the electric field E with the S-polarization but propagates toward the grating 450 at an rotation angle φ that is substantially equal to ninety

20 degrees (90°). Since the incident energy 500 is substantially in parallel with the grating lines 450', the electric field E is substantially perpendicular to the grating lines 450' as shown in Fig. 13B.

[0085] Similarly, Figs. 13C-D illustrate the incident energy 500 with the electric field E having P-polarization. In the P-polarization, the electric field E is substantially in the plane of

25 incidence PI (shown in Fig. 9) and has a tangential component and a perpendicular component. The tangential component is substantially parallel to the surface 420; whereas, the perpendicular component is substantially perpendicular to the surface 420. In Fig. 13C, the incident energy

500 is shown as propagating toward the grating 450 at an rotation angle ϕ that is substantially

equal to zero degrees (0°). Since the incident energy 500 is substantially perpendicular to the

grating lines 450', the electric field likewise is substantially perpendicular to the grating lines

450' and has a field component E' that is substantially normal to the surface 450. The incident

5   energy 500 that propagates toward the grating 450 at an rotation angle ϕ that is substantially

equal to ninety degrees (90°) is illustrated in Fig. 13D. Here, the incident energy 500 is

substantially parallel to the grating lines 450' such that the electric field E also is substantially

parallel to the grating lines 450'. In the manner discussed above with reference to Fig. 13C, the

field component E' of the electric field E is substantially normal to the surface 450.

10   [0086]   Another embodiment of the metrology system 100 (shown in Fig. 2) is illustrated as

the metrology system 100" in Figs. 14A-B. In the manner discussed in more detail above with

reference to the metrology system 100' (shown in Fig. 7), the metrology system 100" includes a

measurement system 200" that is coupled with, and configured to communicate with, a

processing system 300" as shown in Fig. 14A. Being configured to characterize a three-

15   dimensional structure 410 (shown in Fig. 2) formed on a specimen 400, the metrology system

100" can rotate the measurement system 200" relative to the specimen 400 while the

measurement system 200" directs a beam of incident energy 500 toward the specimen 400. As

illustrated in Fig. 14A, the rotation of the measurement system 200" relative to specimen 400 is

performed along an axis of rotation AR that preferably is substantially perpendicular to an

20   external surface 420 of the specimen 400 and intersects the structure 410. Propagating toward

the specimen 400 substantially at an angle of illumination θ relative to the axis of rotation AR,

the incident energy 500 reflects from the surface 420 as reflected energy 500', at least a portion

of which propagates toward the measurement system 200".

[0087]   The measurement system 200" also is configured to receive the reflected energy 500'

25   and to produce data signals (not shown) therefrom, providing the data signals to the processing

system 300". As the relative rotation continues, the measurement system 200" receives reflected

energy 500' associated with each of a plurality of rotation angles ϕ and produces additional data

signals, which likewise are provided to the processing system 300". Thereby, a spectrum of data

signals is produced with respect to the rotation angle ϕ. Receiving the spectrum of data signals,

in whole or in part, from the measurement system 200", the processing system 300" is

configured to perform an analysis of the data signals to determine whether the structure 410 has

5   any defects, such as yield limiting deviations or other processing defects. The processing system

300" can analyze the data signals in any suitable manner, such as by comparing the data signals

with one or more mathematical models (not shown) of the structure 410.

[0088]   As shown in Fig. 14A, the measurement system 200" comprises an energy source

210, an energy detector 220, and a rotation system 700, each being provided in the manner

10   discussed in more detail above with reference to Figs. 3, 4A-B, 5A-B, and 7. Typically being

coupled and preferably being substantially fixedly coupled, the energy source 210 and the energy

detector 220 are approximately uniformly disposed about, and substantially in axial alignment

with, the axis of rotation AR. Thereby, the rotation system 700 is configured to rotate the energy

source 210 and the energy detector 220 around the axis of rotation AR relative to the specimen

15   400.

[0089]   The measurement system 200" further includes a beam-formation system 215" and an

energy-collection system 225. In the manner described above with reference to Figs. 4A-B, the

beam-formation system 215" is disposed substantially between the energy source 210 and the

specimen 400 and is configured to receive output energy 510 from the energy source 210 and to

20   convert the output energy 510 into the beam of incident energy 500. The energy-collection

system 225 is provided in the manner described above with reference to Figs. 5A-B and is

disposed substantially between the specimen 400 and the energy detector 220. The energy-

collection system 225 is configured to receive the reflections of the incident energy 500 from the

specimen 400 and to convert these reflections into the reflected energy 500' in the manner

25   described above with reference to Figs. 5A-B. Being shown in Fig. 14A as being separate from

the energy source 210 and the energy detector 220, respectively, for purposes of illustration, it

will be appreciated that the beam-formation system 215" can be disposed substantially within the

energy source 210 as illustrated in Fig. 4A, and/or the energy-collection system 225 can be

disposed substantially within the energy detector 220 as illustrated in Fig. 5A.

[0090] Upon receiving the output energy 510 from the energy source 210, the beam-

formation system 215" is configured to divide the output energy 510 into a plurality of

5   components and to modulate each component at a preselected frequency. The modulated

components then are recombined to form the beam of incident energy 500. One embodiment of

the beam-formation system 215" is illustrated in Fig. 14B. As shown in Fig. 14B, the beam-

formation system 215" is configured to divide the output energy 510 into two components. If the

output energy 510 comprises electromagnetic energy, for example, the components can be a S-

10   polarized component and a P-polarized component of the output energy 510.

[0091] The beam-formation system 215" includes a polarization system 215A that is

configured to receive the output energy 510 to provide polarized output energy 510A. A beam-

splitting system 215B is coupled with the polarization system 215A and can receive the polarized

output energy 510A, dividing the polarized output energy 510A into first and second polarized

15   output energy 510B, 510C. The first polarized output energy 510B is provided to a first

modulation system 215C, which is configured to modulate the first polarized output energy 510B

at a first preselected modulation frequency F1, and then is provided to a beam-combining system

215H via a mirror 215D.

[0092] The polarized output energy 510C is provided to a wave plate 215E. Preferably

20   comprising a one-half wave plate, the wave plate 215E is configured to modify the polarization

of the polarized output energy 510C, such as by approximately ninety degrees (90°). The

polarized output energy 510C, as modified, is provided to a second modulation system 215G via

a mirror 215F. The second modulation system 215G is configured to modulate the second

polarized output energy 510C at a second preselected modulation frequency F2 and to provide

25   the second polarized output energy 510C, as modified and modulated, to the beam-combining

system 215H. The beam-combining system 215H combines the modulated first polarized output

energy 510B with the second polarized output energy 510C, as modified and modulated, to form the resultant beam of incident energy 500.

[0093]   Returning to Fig. 14A, the resultant beam of incident energy 500 is directed toward the specimen 400 in the manner described in more detail above. The reflected energy 500' is

5   received by the energy-collection system 225, which analyzes the polarization of the reflected energy 500' before providing the reflected energy 500' to the energy detector 220. Since the beam of incident energy 500 includes two polarization states, each being modulated at a different preselected frequency, the reflected energy 500' received by the energy detector 220 substantially comprises two sets of information. In other words, each polarization state may be

10   processed by the measurement system 200 as two separate operands.

[0094]   Many operations therefore can be performed on the reflected energy 500' to produce the data signals. For example, the two polarization states can be interfered to derive interference signals (not shown) that comprise a difference in phase between the signals comprising the two polarization states. To interfere the two polarization states of the reflected energy 500', the

15   energy-collection system 225 can analyze the reflected energy 500' at an angle of substantially forty-five degrees (45°). Thereby, the interference signals are provided with frequencies that are substantially equal to the sum and/or the difference of the first and second preselected modulation frequencies F1, F2. Once produced, the interference signals can be provided to the processing system 300" as the data signals. It will be appreciated that any suitable one-operand

20   and/or two-operand operation can be performed on the two polarization states of the reflected energy 500'. Illustrative two-operand operations include addition, subtraction, ratio, and/or logic operations, such as AND, OR, NAND, NOR, and/or XOR.

[0095]   In the manner discussed in more detail above with reference to Figs. 7A-B, the processing system 300" can be provided in any suitable manner and, as shown in Fig. 14A, is

25   provided substantially in the manner described above with reference to Fig. 7B. The processing system 300" is configured to receive the data signals from the measurement system 200" and includes a data acquisition system 310", a central processing system 320", a memory system

330" and a modeling system 340". Each of the data acquisition system 310", the central

processing system 320", the memory system 330" and the modeling system 340" are provided in

the manner described in more detail above with regard to Fig. 7B.

[0096]   The processing system 300" further includes first and second frequency generators

5   350, 360. The first and second frequency generators 350, 360 can comprise any suitable type of

frequency generator and are configure to generate the first and second preselected modulation

frequencies F1, F2, respectively. Although illustrated as being disposed within the processing

system 300", the first and second frequency generators 350, 360 can be separate from the

processing system 300" and, as desired, may be disposed within the measurement system 200".

10   The first and second frequency generators 350, 360 are coupled with, and configured to provide

the first and second preselected modulation frequencies F1, F2 to, the beam-formation system

215" and the data acquisition system 310".

[0097]   The processing system 300" can process the interference signals and/or the data

signals provided by the measurement system in the manner discussed in more detail above with

15   reference to Fig. 7B. Preferably, the data acquisition system 310" comprises a synchronous data

acquisition system and is configured to lock the interference signals and/or the data signals to

any of the frequencies that correspond to the interference signals and/or the data signals. The

frequencies that correspond to the interference signals and/or the data signals include the first

modulation frequency F1, the second modulation frequency F2, a sum of the first and second

20   modulation frequencies F1, F2, and a difference between the first and second preselected

modulation frequencies F1, F2. Such a method for acquiring the interference signals and/or the

data signals sometimes is referred to as "lock-in detection."

[0098]   Although the metrology system 100" is shown and described as being in the bright

field detection configuration in the manner discussed above with reference to Fig. 6B, it will be

25   appreciated that the metrology system 100" likewise can be provided in the dark field detection

configuration in the manner described in more detail above with reference to Fig. 6A.

Furthermore, if the beam of incident energy 500 was not modulated in the manner described

above with reference to Fig. 14B, the metrology system 100" is configured to analyze simple

reflectivity data as a function of the rotation angle φ when provided in the bright field detection

configuration. Likewise, when provided in the dark field detection configuration, the metrology

system 100" is configured to analyze simple scattering data as a function of the rotation angle φ

5 if the beam of incident energy 500 was not modulated.

[0099] Radio or microwaves have a substantially long wavelength λ relative to the structures

comprising the metrology system 100 and/or to any aperture or lens with reasonable size. As

such, the directivity of the incident energy 500 can become lost such that the incident energy 500

appears to be coming from a point source. For this reason, the metrology system 100 can further

10 include a near field cavity system 900 as shown in Fig. 15. An exemplary near field cavity

system 900 is disclosed by Ash et al in 1974, in Nature, the disclosure of which is hereby

expressly incorporated herein by reference. The near field cavity system 900 forms a microwave

cavity 910 that is configured to communicate with a sub-wavelength hole (or aperture) 920

defined by the near field cavity system 900.

15 [00100] The near field cavity system 900 is configured to provide radiation signals 930.

These radiation signals 930 preferably are evanescent and decay substantially exponentially. In

operation, the metrology system 100 can detect the presence of defects in the structure 410 by

measuring an input impedance (not shown) of the cavity 910. The input impedance of the cavity

910 can be readily measured. When the structure 410 includes a defect (not shown), the near

20 field cavity system 900 can detect the defect, indicating the detection of the defect via a change

in the input impedance.

[00101] When the specimen 400 is vibrated at a preselected frequency and axially relative to

the axis of rotation AR, the input impedance of the cavity 910 can be modulated at the

preselected frequency. The measurement system 200 and/or the energy detector 220 of the

25 metrology system 100 can be locked on the preselected frequency. Since the direction of the

electric field E outside of the cavity 900 is a function of the modes within the cavity 900. As a

result, when the cavity 900 is rotated about the axis of rotation AR, a spectrum of input

impedances can be obtained with respect to the rotation angle ϕ.

[00102]   Although the various embodiments have been described with reference to optical

waves and microwaves, it will be appreciated that the various embodiments apply to energy with

5   any wavelength, such as x-rays. When the incident energy 500 comprises x-rays, for example,

the angle of illumination θ should approach an angle of approximately ninety degrees (90°). If

the angle of illumination θ is too large, the reflected energy 500' is approximately six orders of

magnitude down. Therefore, the range of suitable angles of illumination θ comprises a range of

very shallow angles when the incident energy 500 comprises x-rays. To increase the range of

10   suitable angles of illumination θ when the incident energy 500 comprises x-rays, the beam of

incident energy 500 can be modulated at a preselected frequency and synchronous detection can

be performed on the incident energy in the manner described above with reference to the dark

field detection configuration of the metrology system 100 shown in Fig. 6A. Thereby, a signal-

to-noise ratio of the incident energy 500 can be improved for angles of illumination θ that

15   approach approximately ninety degrees (90°) such that the range of suitable angles of

illumination θ can be expanded when the incident energy 500 comprises x-rays.

[00103]   The various embodiments disclosed herein are susceptible to various modifications

and alternative forms, and specific examples thereof have been shown by way of example in the

drawings and are herein described in detail. It should be understood, however, that the subject

20   matter disclosed herein is not to be limited to the particular forms or methods disclosed, but to

the contrary, the all modifications, equivalents, and alternatives are covered that fall within the

spirit and scope of the claims.